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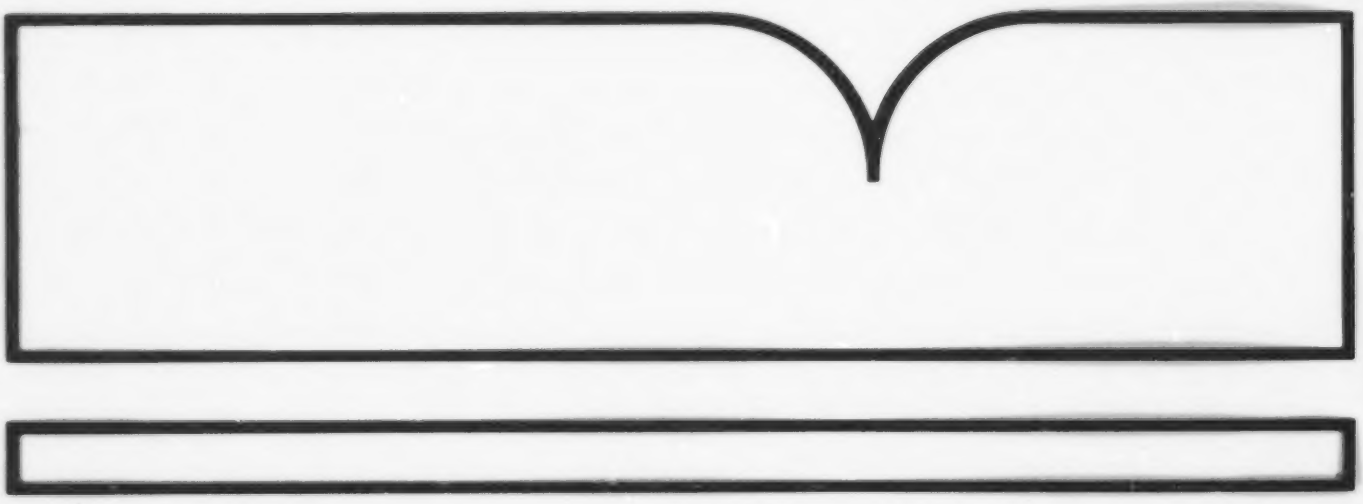

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Clay Liner Construction and Quality Control

By J. Jeffrey Peirce,[1] Goran Sallfors,[2] and Eric Peterson[3]

Abstract: Soil handling and liner construction practices at hazardous waste management facilities are documented. Soil characterizations, processing techniques, construction methods, and quality control of constructed liners are reviewed and compared. Results indicate widely different testing and construction methods at 23 facilities nationwide. Laboratory research indicates that selected clay soils exhibit low hydraulic conductivity to water and certain non-water liquid wastes. This characteristic makes clay soils potentially useful as liner materials at hazardous waste management facilities. Such facilities have been constructed and, although the intended barrier function of the liners is always the same, testing and construction techniques are seen to vary from site to site. The need for parallel laboratory hydraulic conductivity testing and practices in field preparation of clay soils is noted.

Introduction

Laboratory research has shown that clay soils exhibit very low hydraulic conductivity to water at certain levels of compaction and moisture content. This characteristic makes clay potentially useful in landfill liners, which serve as protective barriers between waste leachate and the surrounding environment. Natural clay liners are being and have been constructed in many waste disposal sites both in the US and abroad. Although the intended barrier function of these liners is always the same, testing and construction techniques vary from site to site.

The objective of this paper, therefore, is to gather and document information from industry regarding soil handling and liner construction in the field. Pertinent information includes data on: (1) The characteristics monitored in the soil to be used; (2) the processing of the soil; (3) construction techniques; and (4) quality control on the constructed liner. The methods used to meet the objectives, the results of the study, and conclusions are presented below.

Methods to Meet Objectives

The information was obtained through research of current literature and through telephone contacts. Some of the data are confidential and those sources are given in Table 1 rather than listing them in the references. Soil handling practices in the field are affected by the contrac-

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TABLE 1.—Confidential Contacts

Confidential contact (1)	Site location (2)
4.1	SE U.S.
4.2	SE U.S.
4.3	NE U.S.
4.4	SE U.S.
4.5	NE U.S.
4.6	NE U.S.
4.7	S Central U.S.
4.8	NE U.S.
4.9	NE U.S.
4.10	NE U.S.
4.11	NE U.S.
4.12	NE U.S.
4.13	SE U.S.
4.14	NE U.S.
4.15	NE U.S.
4.16	NE U.S.
4.17	SE U.S.
4.18	NE U.S.
4.19	NE U.S.

tor, the engineer, and the regulatory agency. The contractor performing the construction is the obvious source of information for construction techniques. The engineer typically dictates the design, the soil type used, and the quality control. Finally, the regulatory agency may issue specifications which must be met. The information combined herein was obtained through contacts with these three groups along with published case histories.

Results of Data Collection Activities

The conducted research did reveal a variety of construction and testing methods for clay liners. This is to be expected to some degree considering the variety of applications, which range from hazardous waste landfills to stormwater retention ponds. The results are divided into two sections. The major portion of the research is reflected in Table 2, which tabulates the testing and construction methods site by site. This table is examined below in the first subsection. The second subsection presents information gained from commercial laboratories regarding preparation of soil samples for hydraulic conductivity testing, whose results are contained in Table 3. These data were compiled in order to compare compaction procedures in the laboratory to those in the field.

Testing and Construction

Col. 1 in Table 2 describes the type and frequency of testing done on a clay soil prior to its selection for use in a clay-soil liner. Test samples are often obtained from soil borings, although some are bulk samples

collected by hand. Typically, the soils are analyzed for particle size distribution, compaction (moisture-density curves), and hydraulic conductivity (permeability). Atterberg limits are considered at selected sites. In most cases, hydraulic conductivity tests are conducted on remolded samples. Two sites, one in South Carolina and the other in West Germany (6), however, constructed test areas where the clay was compacted with different equipment at various lift thicknesses. Undisturbed samples were then collected and hydraulic conductivity tests run. In this manner, the engineers were able to determine which construction technique was suitable for their clay. This is potentially useful in practice for clays exhibiting marginal hydraulic conductivities, since field equipment cannot always attain the compaction achieved in the laboratory prior to testing.

Of the sites listed, perhaps the most extensive preliminary soils testing program was employed at the Mexican cooling pond site (1). Not only was a compaction test area constructed as in Germany, but also a test pond measuring 164 × 164 sq ft (50 × 50 m^2) where field permeabilities were measured by filling and measuring water level change. Although the pond was designed to hold water and not hazardous chemicals, the scarcity and subsequent value of water in this area mandated such strict quality assurance measures.

Preliminary testing frequency depends on several factors. Choosing a clay deposit for use as liner material may begin with field observations and a study of local geology by a geologist. If a deposit appears uniform, the sampling frequency would be less than the frequency for a nonuniform deposit exhibiting a variety of soil types.

On a case-by-case basis, soil preparation or processing may be necessary to refine a soil for use in a liner. Such processing could include removal of organic matter or sieving to remove large clods or cobbles. Several sites listed in Table 2 did sieve the soil, but none found removal of organic material necessary. Two of the sites that did sieve used a six in. (0.15 m) bar screen for this purpose. The aforementioned cooling pond construction in Mexico involved soil preparation by homogenizing, wetting, and curing the soil prior to compaction. Auvinet and Espinosa did not discuss in their paper the method of homogenizing (1), however, wetting was accomplished by thoroughly mixing the soil when adding water and letting it cure for approximately one week. This curing process was not employed by any of the other sites in Table 2 due to climatological factors. None of the other sites are located in such arid regions, and this step prior to spreading and compacting is generally not determined to be necessary to contractors.

Entries in Table 2, Col. 5, indicate the overall thickness of the clay liner and also the thickness of the individual lifts compacted to form the liner. All of the sites included in the research utilized lifts in the 6–12 in. (0.15–0.30 m) range. The total liner thickness varied from 1–13 ft (0.3–4.0 m) depending on the type of application, location, and overall liner design. Data from the hazardous waste sites reveal greatly different thicknesses: from 2–13 ft (0.6–4.0 m). The overall liner design may provide an explanation here. The sites with the thinner layers (i.e. 2–5; 0.6–1.5 m) were constructed in conjunction with two synthetic membrane liners. For instance, the site employing a 5 ft (1.5 m) clay layer was

TABLE 2.—Handling, Preparation and Compaction of Clay

Location (1)	Type (hazardous or other) (2)	Preliminary soil tests/frequency (3)	Soil preparation (4)
Southeastern US	Hazardous	Information not available	None
South Central US	Hazardous	Permeability and compaction from 12 borings taken from ~25 acre (10 ha) site	Remove sand seams
Southeastern US	Hazardous	Information not available	Breakup clumps 3 in. (75 m) and remove "undesirables" soil seams
Northeastern US	Hazardous	Compaction, grain size, and hydraulic conductivity	None
Northeastern US	Hazardous	3 year sampling program 60 hydraulic conductivity 100 Atterberg limits and grain size tests Weekly moisture and density	None
Germany (6)	Hazardous	Hydraulic conductivity from field compaction test areas	Clods >8 in. (0.2 m) broken down during excavation
Northeastern US	Hazardous	Compaction, hydraulic conductivity, Atterberg limits, and grain size from 1 bag sample per 15,000 c.y.	None
Northeastern US	Hazardous	Compaction, hydraulic permeability, Atterberg limits, and grain size from 1 bag sample per 15,000 c.y.	None
South Central US	Hazardous	Atterberg limits, and grain size 1 a per 500 c.y. (400 m^3)	None
South Central US	Hazardous	None	None
Northeastern	Other	Compaction, grain size, and hydraulic conductivity	Seive with 6 in. (0.15 m) screen

Soils Used for Construction of Lines in the Field

Liner/lift thickness (5)	Moisture control (6)	Compaction equipment (7)	Constructed liner size (8)	Liner tests/ frequency (9)
5 ft (1.5 m) total; 6–9 in. (0.15–0.23 m) lists	Not necessary	Bulldozer	2–4 acres (0.8–1.6 ha)	Density and moisture with NDM
2 ft (0.6 m) total recompacted on existing clay; 6 in. (0.15 m) lifts	Drying only by pumping	Bulldozer, sheepsfoot roller	~1 acre (0.4 ha)	Density and moisture with NDM on 100 ft (30 m) grid
10–25 ft total; (3 to 7.6 m) recompacted on existing clay; 6 in. (1.15 m) lists	Wet stockpile	Scrapers, bulldozer, sheepsfoot roller	~7 acres (~3 ha)	Density and moisture with NDM or sand cone 1 test per layer on 75 ft (23 m) grid Hydraulic conductivity in lab with chemical permeant Hydraulic conductivity in field with standpipe percolation test
5 ft (1.5 m) total; 6 in. (0.15 m) lifts	Spray and check with NDM	Bulldozer	4–5 acres (1.6–2 ha)	Hydraulic conductivity per 3 acre-ft (0.4 ha-m) Density and moisture on 50 ft (15 m) grid with ~ NDM
10 ft (3 m) total; 1 ft (0.3 m) lifts	Not necessary	Vibratory sheepsfoot roller	~14.7 acres (6 ha)	Density and moisture with NDM
Total up to 13 ft (4 m) depending on thickness of existing clay layer; 7–9 in. (0.18–0.25 m) lifts	Not necessary	Smooth drum roller	~17.3 acres (7 ha)	Density, moisture, and hydraulic conductivity at random intervals
5 ft (1.5 m) total; 9–12 in. (0.23–0.30 m) lifts	Spray spreaded clay as necessary	Smooth drum vibratory roller, sheepsfoot roller	~1.4 acres (0.6 ha)	Density and moisture with NDM on 50 ft (15 m) grid 3 hydraulic conductivity per 10 acre (1.2 ha)
10 in. (0.25 m) total; 9–12 in. (0.23–0.30 m) lifts	Not necessary	Vibratory sheepsfoot	~1.4 acres (0.6 ha)	Density and moisture with NDM on 50 ft (15 m) grid 3 hydraulic conductivity per 10 acre (1.2 ha m)
2 ft (0.6 m) total; 6–8 in. (0.15–0.20 m) lifts	Information not available	Information not available	6 cells ~5 acres (2 ha) each	Density and moisture with NDM
2 ft (0.6 m) total; recompacted on existing clay; single lift	None	Undecided to date	2 acres (0.8 ha)	None
2 ft (0.6 m) total; 8 in. (0.2 m) lifts	Spray soil check with NDM	Sheepsfoot roller in 8 passes	2 acres (0.8 ha)	Moisture and density with NDM on

TABLE 2.—

(1)	(2)	(3)	(4)
Northeastern US	Other	Compaction, grain size, hydraulic conductivity, and Atterberg limits from 2 bulk samples	None
Northeastern US	Other	Compaction, grain size, and hydraulic conductivity, from 30–35 borings in 10 acres (4 ha)	None
Northeastern US	Other	Information not available	None
Canada (4)	Other	Hydraulic conductivity (with fresh water and brine), compaction, and Atterberg limits	Breakup lumps and remove sand, silt and gravel pockets
Northeastern US (5)	Other	Compaction and hydraulic conductivity	None
Mexico (1)	Other	Information not available	Mix soil
South Central US (3)	Other	Compaction, hydraulic conductivity and Atterberg limits	Information not available
Northeastern US	Other	Information not available	None
Northeastern US	Other	Compaction and hydraulic conductivity	Sieve
Northeastern US	Other	Compaction, grain size, and hydraulic conductivity from split spoon samples from 200 ft (60 m) grid	None
Northeastern US	Other	Compaction, hydraulic conductivity (at natural water content), grain size, and Atterberg limits	None
Northeastern US	Other	Compaction, hydraulic conductivity (at natural water content), grain size, and Atterberg limits	None

Note: NDM = Nuclear Density Meter, c.y. = cubic yard (0.84 m^3)

overlain by 30 mil synthetic (plastic) liner and 80 mil high density polyethylene (HDPE) with two more feet (0.6 m) of compacted clay on top. The site with the 10 ft (3 m) compacted clay layer, which represents an intermediate thickness in this comparison, was overlain by one synthetic membrane (80 mil HDPE) with an additional 1 ft (0.3 m) of compacted clay on top. Finally, the site with the thickest clay layer [13.1 ft (4 m)]

Continued

(5)	(6)	(7)	(8)	(9)
				100 ft (30 m) grid 1 permeability per acre (0.4 ha)
1 ft (0.3 m) total; 4 in. (0.2 m) lifts	Not necessary	Vibratory sheepsfoot roller with rectangular teeth in 5–10 passes	2.5 acres (1 ha)	1 permeability test per 40,000 s.f. (3,700 m^2)
2 ft (0.6 m) total; 6 in. (0.15 m) lifts	Not necessary	Vibratory smooth drum roller in 10–15 passes	3–4 acres (1.2–1.6 ha)	1 permeability test per acre (0.4 ha)
10 ft (3 m) total excavated in existing clay	Spray if dry, air dry if wet	Bulldozer	~3.5 acres (1.5 ha)	1 soil boring to check thickness per 3.5 acres (1.5 ha) 1 permeability test per 60,000 s.f. (0.5 ha)
3 ft (0.9 m) total; 7.9 in. (0.2 m) lifts	Information not available	Information not available	~7.9 acres (~3 ha)	Information not available
Information not available	Information not available	Sheepsfoot roller	Information not available	Density and moisture with NDM
19.7 in. (0.5 m) total; 7.9 in. (0.2 m) lifts	Sprayed	13 ton (12 tonne) farm tractor with 8 passes	741 acres (300 ha)	Full scale field test for hydraulic conductivity by filling test pond and measuring water level
1 ft (0.3 m) total; 6 in. (0.15 m) lifts	Not necessary	Sheepsfoot roller	2 acres (0.8 ha)	Hydraulic conductivity checked by filling pond
1 ft (0.3 m) total; 6 in. (0.15 m) lifts	Spray spreaded soil	Bulldozer	~3 acres (1.2 ha)	Hydraulic conductivity 60,000 s.f. (1.4 ha)
6 in.–1 ft (0.15–0.30 m) total in one lift	Spray as necessary	Tamp with backhoe bucket	4,000 ft (1,200 m) long trench lined with clay	1 NDM test for density every 667 ft (20 mm)
2 ft (0.6 m) total; 6–8 in. (0.15–0.20 m) lifts	Spray and mix with disk	Sheepsfoot roller in 8 passes	7 acres (3 ha)	Moisture and density with NDM Hydraulic conductivity test per 1.5 acres (0.6 ha)
1 ft (0.3 m) total; 1 ft (0.3 m) lift	Scarify to air dry	Padfoot roller in 4 passes	1 acre (0.4 ha)	Density and moisture with NDM
2 ft (0.6 m) total; 1 ft (0.3 m) lift	Scarify to air dry	Padfoot roller in 4 passes	3 ponds totaling 1 acre (0.4 ha)	Density and moisture with NDM

and those excavated in existing clay formations rely solely on the natural clay as an impermeable barrier (6).

Approximately half of the locations utilized a compactor with teeth such as a sheepsfoot roller. The other sites used smooth drum rollers, vibratory or nonvibratory, or simply a heavy bulldozer. The tabulated information indicates that roughly 8–10 passes with a sheepsfoot type

TABLE 3.—Commercial Laboratory Preparation of Clay Samples for Hydraulic Conductivity Testing

Materials and preparation (1)	Clay (2)	Commercial lab #1 (3)	Commercial lab #2 (4)	Commercial lab #3 (5)
Clay	Type	Field clays mostly kaolinite and illite	Field clays	Field clays (CH)
	Excavation procedure	Test pits with backhoe	Obtained from client	Backhoe-bulk sample from stockpile
	Handling and storage	Double wrap of plastic and burlap	Airtight plastic bags	Bulk samples as received
Processing	Size control	Hand pick or break lumps >3/4 in. (18 mm)	Number 4 sieve	Hand pick
	Organic control	Hand pick	Hand pick weeds and roots	Hand pick
	Moisture control	Immediately test for moisture content	Prevent drying	Prevent drying
	Homogenity	Visual inspection—cut and quarter large samples	Time representative sample from bulk	Representative sample from bulk
	Additives	None	None	None
Preparation	Wetting substance	By priority 1. site water 2. tap 3. distilled	As received	Deionized water
	Wetting procedure	Mint bottle and mixing	As received	Water added in small increments. Allow to absorb overnight
	Percent moisture	Optimum moisture plus 1–2%	As received	Optimum
	Size control	1/4 in. sieve (6 mm)	As received	Number 4 sieve
Compaction	Test vessel dimensions	2.8 in. diam (70 mm) 3–5 in. height (75–125 mm)	4 in. mold (10 cm)	Shelby tube 2.8 in. diam (70 mm)
	Compaction procedures	Standard proctor / Modified proctor	Standard or modified	Standard or modified
	Lift depth	Varies / Varies	Approx 1 in. (25 mm)	2-1/2 in. (63 mm)
	Number of lifts	3 / 5	3 / 5	3
	Scarify lift	Yes	Yes	Yes
Testing	Perflush substance	Depends on project; site, tap, distilled water	Demineralized water	Deionized water
	Head	50–100 gradient (in./in.)	100 psi (700 kPa)	Variable
	Perflush time (pore volumes)	1 pore volume	No set number	3 runs—until constant K achieved
	Chemical permeants tested	Organic and inorganic	1.5 pH H_2SO_4, brine boiler wastewater	N.A.

compactor is sufficient to achieve the desired hydraulic conductivity, depending on many factors including lift thickness and moisture content. The equipment necessary for compaction varies with the soil characteristics. One site using a vibratory compactor with rectangular teeth was only attaining 81% modified Proctor density, which resulted in hydraulic conductivities in the 10^{-8} cm/s range as measured in the lab from undisturbed samples. Where smooth drum rollers were used, the clay was scarificed between lifts to inhibit the formation of a distinct interface.

The size or area of the liner constructed basically ranged from 1.5–4 acres (0.6–1.6 ha). Smaller sites may construct a liner for the entire landfill in one time period, but most sites constructed their liners in sections as needed to avoid prolonged exposure and drainage problems. Exceptions included the West German landfill where a 17 acre (7 ha) liner was constructed as a whole. The liner here was never exposed long as immediately following completion of the uppermost lift, a blanket of filter gravel sandwiched between two geotextile liners was placed on top (6). In Mexico, a 741 acre (300 ha) cooling pond was constructed in a manner to protect the clay liner against dessication and erosion by covering it with a gravel layer and flooding completed sections as soon as possible (1).

In construction of a clay liner, the obvious criterion to be met is an upper limit on hydraulic conductivity as reflected in Col. 9 of Table 2. This research has shown that two methods are generally used by industry to test for hydraulic conductivity. One method is to take undisturbed samples, such as with a shelby tube, of the completed liner and have this analyzed directly for hydraulic conductivity. The other method most often used is testing for density and moisture content using a nuclear density meter in the field. The results of this test can be correlated to the results of the preliminary tests to obtain an indication of hydraulic conductivity. Several sites use both methods for quality control. The most common range of testing frequency was one hydraulic conductivity test per 1–1.5 acres (0.4–0.6 ha).

Generally, liner testing was conducted to indicate if the desired or required hydraulic conductivity had been achieved, usually 1×10^{-7} cm/s (1.25 in./yr) or less as required by the regulatory agency. Exceptions to this rule include Denmark, where the recommended hydraulic conductivity for a landfill liner is less than or equal to 1×10^{-8} cm/s (0.13 in./yr) (2) and West Germany where the site listed in Table 2 was required to have a liner hydraulic conductivity of less than 1×10^{-6} cm/s (1 ft/yr) (12).

Another parameter often dictated by regulation is the degree of compaction. The aforementioned Danish recommendations include a required compaction of 95% standard Proctor or more (2). Pennsylvania uses the same figure in their requirements (9). New Jersey regulators generally seek 95% modified Proctor achieved although this requirement may be waived under certain circumstances (7). Such circumstances include intermediate liners where a clay liner is constructed on existing refuse, which does not afford a firm enough foundation to achieve such densities.

Possible Improvement of Current Practice

Current practice for liner construction is fairly consistent regarding preliminary soil tests of liner material, lift thicknesses, and final control of liner. However, it seems a crucial point sometimes may be overlooked, i.e., the checking and preparation of the soil that goes into the liner. It is imperative to remove pockets of sand and other coarse material, as well as clearly visible quantities of organic material. The homogeneity of a liner, and thereby its ability to restrict flow, would prob-

ably also be improved if some sort of size control was used, in order to remove large lumps. This will represent a minor cost increase but also an improved performance for some liners.

Another question that deserves attention is that of moisture control during compaction. Most of the interviewed persons said that there was no need for any adjustment of the water content. No doubt the required compaction and hydraulic conductivity could be obtained by compacting at the natural water content. The given criteria for the hydraulic conductivity is, however, a maximum value; the lower the hydraulic conductivity the better the liner. In many of the cases, it is plausible that a lower hydraulic conductivity could be obtained if the water content was altered to be a few percent above optimum.

Another area, which probably needs more research attention is that of quality control: how many samples should be taken of the completed liner, and at what spatial variation and what should the level of acceptance be.

Commercial Laboratories

Selected commercial laboratories were interviewed to document their handling and preparation of clay samples delivered to them for hydraulic conductivity testing. Commercial laboratories represent an important component of the clay selection process in liner design. The data generated by such facilities are often the deciding factor for judging the suitability of a soil for use in a liner. Table 3 lists the results from the three commercial laboratories interviewed.

Case history research by Daniels (3) has already shown the possibility of large discrepancies between hydraulic conductivities measured in the lab and those measured in the field for thin clay liners [1–2 ft (0.3–0.6 m) thick]. Based on four case histories . . . "the actual hydraulic conductivities of the clay liners were found to be 10 to 1,000 times larger than values obtained from laboratory tests on either undisturbed or recompacted samples of the clay liner" (3). For recompacted samples these differences are partly attributed to laboratory compaction effort, compaction water content, clod size, and organic matter content not matching field conditions.

Regarding clod size, Table 3 reveals that all three labs interviewed control the clay sample by handpicking or sieving out the larger soil fraction. This practice can lead to lower estimates in the lab for hydraulic conductivities in two ways: (1) Clay composed of smaller clods compacts tighter; and (2) smaller clods allow more thorough wetting for optimum moisture (7). Some clay liner projects do sieve the clay in the field, but unless this is done, size control should not be performed in the lab. Similarly, organic matter is routinely removed by the interviewed labs, but not practiced in the field by any of the sites in Table 2. The presence of organic matter such as roots provides the permeant with a pathway through the otherwise relatively impermeable soil.

Compaction water content was mentioned earlier in terms of moisture control in the field. Obviously, water content is much easier to control and measure in the lab than it is in the field. Finally, compaction effort must be duplicated in the field to achieve similar hydraulic conductivi-

ties to those measured in the lab. In addition to preliminary soil testing, laboratories may also perform the crucial function of hydraulic conductivity testing on undisturbed samples from the constructed liner. In many instances, the results of these tests are necessary to meet specifications required by regulation. Daniel's findings, however, suggest that hydraulic conductivity testing results from undisturbed samples of thin clay liners are also subject to large discrepancies from actual or field measured hydraulic conductivities. This can be attributed to unrepresentative samples not containing fissures or desiccation cracks, which may be present in the field, or lab error from the use of excessive gradients or improper permeants (3). Of the three labs interviewed, two use site water or various chemicals to best reflect field conditions.

The most marked difference of practice between the three laboratories is that of the water content used for hydraulic conductivity. One compacts the sample with the water content it has in the field, one compacts at optimum and the third a few percent above optimum. The three laboratories could very well end up with quite different hydraulic conductivities for the same clay. Which procedure is to be preferred strongly depends on how the clay is treated in the field, which again points out the importance of moisture control in the field.

Conclusions

Based on the results of this research, the following conclusions are drawn:

1. Clay liner construction and testing methods differ from site to site according to factors imposed by the design engineer, the regulatory agency, the contractor, site location, and soil characteristics.
2. Uncompacted lift thicknesses of 6–12 in. (0.15–0.3 m) appear to be widely accepted in the field for best compaction of a clay liner.
3. No consistent thickness for clay liners is evident. This parameter varies with soil availability and soil characteristics on a site-by-site basis.
4. Although moisture content is an important parameter in achieving minimum hydraulic conductivity through compaction, most clay liner construction programs do not include any measurement of this parameter. In general, the contractor relies on visual judgment for moisture control.
5. No standard procedure appears to exist for wetting clays that are too dry for compaction.
6. The importance of protecting a clay liner from desiccation appears to be recognized by contractors in the field.
7. Sheepsfoot rollers are most often used for compacting clay, although other equipment such as bulldozers or smooth drum rollers are also employed.
8. Two types of testing are most common for liner quality control: (1) Checking moisture and density with a nuclear density meter during and after construction; and (2) undisturbed soil sampling for hydraulic conductivity testing of the completed liner.
9. Field hydraulic conductivity tests are rarely used to check the integrity of a clay liner.

10. Soil testing laboratories sometimes prepare soil samples in a manner that does not reflect actual field conditions.

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